

# NASA TECHNICAL MEMORANDUM

NASA TM X- 74039

NASA TM X- 74039

(NASA-TM-X-74039) HYPERVELOCITY IMPACT  
TESTS ON SPACE SHUTTLE ORBITER THERMAL  
PROTECTION MATERIAL (NASA) 21 p HC A02/MF  
A01 CSCL 13M

N77-27402

G3/37 Unclass  
35508

## HYPERVELOCITY IMPACT TESTS ON SPACE SHUTTLE ORBITER THERMAL PROTECTION MATERIAL

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June 1977

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# HYPERVELOCITY IMPACT TESTS ON SPACE SHUTTLE ORBITER THERMAL PROTECTION MATERIAL

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## SUMMARY

Hypervelocity impact tests were conducted to simulate the damage that meteoroids will produce in the Shuttle Orbiter leading edge structural subsystem material. The nature and extent of the damage is reported and the probability of encountering meteoroids with sufficient energy to produce such damage is discussed.

## INTRODUCTION

The Space Shuttle Orbiter is a large spacecraft and will spend a considerable amount of time in space and, therefore, can be expected to be struck by larger meteoroids than previous manned spacecraft. The damage that these meteoroids will produce in the complex materials of which the Shuttle Orbiter is constructed can be understood only by conducting hypervelocity impact tests because theories of hypervelocity impact damage have been applied successfully only to homogeneous materials. In the NASA design criteria monograph for meteoroid protection (see ref. 1) the only penetration equations given are those to calculate penetration damage in a simple homogeneous metal sheet. For any other material or any other configuration, the recommended practice is to test the material in the laboratory at the highest impact speed attainable and to scale the tests to meteoroid impact conditions by assuming that particles with equal kinetic energy create equal damage.

The Shuttle Orbiter leading-edge structural subsystem (LESS) material is made of reinforced carbon carbon laminate material with a diffused silicon carbide coating for oxidation protection. This complex composite material has many interfaces between and within the layers of woven material, and certainly falls into the category of materials that must be tested to determine damage characteristics.

The damage that meteoroids will inflict on the LESS material is a concern to the spacecraft designers because this material will be used on the nose and leading edge of the Shuttle Orbiter and is intended to provide thermal protection during reentry.

Some very brittle materials, like beryllium, crack during hypervelocity impact, the crack running from the impact site to the edge of the specimen, (see ref. 2). If the LESS material on the Shuttle Orbiter cracked in that manner, large sections of the material might be lost from the spacecraft. It is suspected that, for some cases, the cracking is caused by stress concentrations that are created by the way the material is supported, while in other cases the cracking is simply a result of the material properties and would occur even if the material were floating freely.

The purpose of the present test program was to produce hypervelocity impact damage in specimens similar to that expected from meteoroids so that the specimens could subsequently be tested in arc heated facilities to evaluate the degradation in thermal performance. In this report only the nature and extent of the hypervelocity impact damage is considered. The degradation in thermal performance as a consequence of the damage is not addressed.

### TEST SPECIMENS

The specimens tested were discs, having a diameter of 72 mm, a thickness of  $5.0 \text{ mm} \pm 0.1 \text{ mm}$ , a mass of about 34 g, and an overall density of  $1.7 \text{ g/cm}^3$ .

### TEST PROCEDURE

The projectiles were launched using a small light-gas gun. Nylon projectiles were launched directly from barrels of the same diameter as the projectiles, (that is, sabots were not used). Photographs taken of the nylon projectiles in flight showed no evidence of ablation during the launch. Glass projectiles were placed on the front of nylon sabots and launched from a 1.52-mm diameter launch tube. In this case ablation is not a concern, because the sabot prevents the gases from reaching the projectiles. Glass projectiles, however, are fragile and sometimes shatter during the launch. Photographs taken of the glass projectiles in flight during these tests showed that they all remained intact. The two photographs taken of the nylon projectile fired at specimen 3-73 at two different positions along the flight path are shown in figure 1(a). The velocity of the projectile was determined from the distance moved in the time interval between photographs. The two photographs of the glass projectiles launched at specimen 3-74 are shown in figure 1(b). Three glass projectiles, each 0.27 mm in diameter, were placed on the sabot for this run. Only one projectile struck the specimen. The sabot can also be seen in these photographs. The sabot and the projectiles separate slightly during flight and the sabot is stopped by a baffle located between the gun and the target.

The specimens were mounted in a foam target holder to avoid concentrated stresses that might cause the specimen to crack. This was done to determine if the LESS material had an inherent tendency to crack during hypervelocity impact. A photograph of the target holder is shown in figure 2. The targets were positioned so that the impacts would be normal to the surface of the specimens. The tests were conducted in a test chamber that was evacuated to a pressure of  $13 \text{ N/m}^2$ .

#### TEST RESULTS

Nine tests were conducted. The results of the tests are shown in table I. The kinetic energy of the projectiles varied from 0.2 J to 74 J. An attempt was made to strike specimen 3-71 with a 0.1 J projectile, but trash struck the specimen, damaging it more extensively than the projectile would have.

Only the front surface was cratered when the impact energy was 3 J, or less. Photographs of the front surface of the four specimens which were damaged only on the front surface are shown in figure 3. At 3 J a trace of the black carbon interior was exposed. At lesser energies only the exterior layers were penetrated. The exterior layers have good resistance to penetration but are brittle and spallation occurs around the impact point; see the front surface area damaged in table I. Information on how brittle the material is and how much resistance to penetration it has can be obtained by comparing the damage with that done to cold rolled steel under the same impact conditions. The test using specimen 3-74 provides an excellent comparison. In that test, three glass projectiles were launched (see figure 1(b)). The projectiles were all the same size and were accelerated to the same

velocity. One projectile struck specimen 3-74 while the other two struck the cold rolled steel baffle. The photographs in figure 4, which are at the same magnification, show the damage produced in the specimen and the steel. The area damaged on the LESS material specimen is 6 times the area damaged on the steel. The depth of penetration was about 480  $\mu\text{m}$  in the LESS material and about 240  $\mu\text{m}$  in the steel. That shows good resistance to penetration especially since the LESS material is only about 1/5 as dense as steel.

The impact at 11 J in specimen 3-72 produced an impact crater on the front surface and a spallation crater on the back surface, although there was no hole through the material. Photographs of both sides of specimen 3-72 are shown in figure 5. Notice the similarity in the damage to both sides. Spallation is common in hypervelocity impacts into brittle materials, even in aluminum and steel (see ref. 1), which are not nearly so brittle as the LESS material.

The specimens were completely penetrated when the impact energy was 34 J or greater. The size of the hole is given in table I. The area damaged on the front and back surfaces is also given in table I. Notice that the rear surface was damaged more extensively than the front surface. The shock wave originating at the impact site caused delamination near the back surface when it was reflected from that surface. Much of the delaminated material was lost as detached spall while some remained attached. Photographs of the front and back surfaces of the three specimens which were completely penetrated are presented in figure 6.

A comparison of the penetration resistance of the LESS material with aluminum and steel can be made using the equations in reference 1. The energy required to penetrate the LESS material is greater than 11 J but less

than 34 J. At 5.5 km/s, nylon projectiles in the 11 J to 34 J range can penetrate 2.0 mm to 3.0 mm of aluminum or 1.3 mm to 2.0 mm of steel. The LESS material does not have the penetration resistance of the metals on a thickness basis, but on a weight basis, that is, mass per unit area required to stop projectiles, it is superior to steel.

One of the specimens developed cracks during the hypervelocity impact test. The cracks, which are on the back surface and edge of specimen 3-73, did not cause the specimen to fragment or to lose material. The photographs in figure 7 show two cracks running from the impact site to the edge of the specimen and other cracks perpendicular to these. No attempt was made to determine the depth of the cracks or the degree to which they effect the strength of the material. The impact site on specimen 3-73 was just 15 mm from the edge of the target. The cracking occurred near the shortest path from the impact site to the edge. None of the other specimens showed any evidence of cracking, even though, in two cases, the impact energy was greater than that for specimen 3-73. In these cases, however, the impact sites were 29 mm or more from the edge of the specimen, see table I.

#### DISCUSSION

The impact energies that can be expected from meteoroids striking the LESS material on the Shuttle Orbiter are shown in figure 8. This calculation is based on the NASA meteoroid environment model (see ref. 3). The area of the nose and leading edge of the Shuttle Orbiter was taken to be  $38 \text{ m}^2$ . It was assumed that the nose was pointed in the direction of motion of the spacecraft and, consequently, that the meteoroid flux was four times the average

flux on a randomly oriented surface. That is the maximum flux that a surface can be expected to receive (see ref. 4).

The probability of the LESS material being penetrated on a single mission of 30 days duration is only 0.04 (using 34 J as the energy necessary for penetration). However, over 500 missions of 7 days duration are shown in the 1973 Space Shuttle Traffic Model (see ref. 5). The probability that a penetration will occur on at least one orbiter is about 0.98, almost a certainty. More likely than not, during one of the 500 Shuttle missions, the LESS material will be struck by a meteoroid with kinetic energy in excess of 160 J. Damage like that caused by the 3 J impact must be expected to occur about once during each 30-day mission. Of course, many impacts with kinetic energy in excess of 0.2 J will occur during each mission.

The probability that cracks will be produced in the LESS material on the Shuttle Orbiter was not calculated because the dependence of crack formation on projectile properties and impact conditions is not known. Apparently the proximity of the impact site to an edge is an important factor. If this is the case, then the probability of cracks being produced would also depend on the size of the segments covering the nose and leading edge.



#### REFERENCES

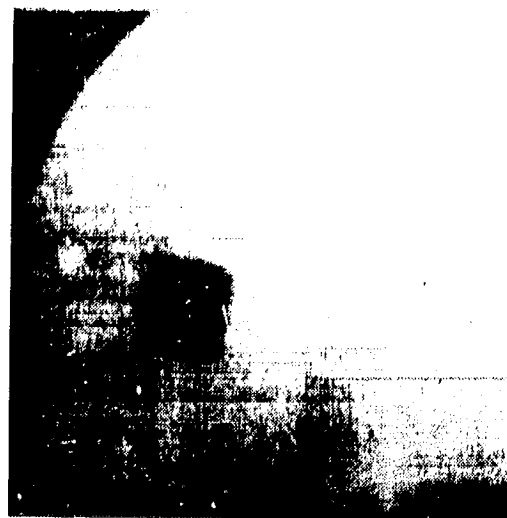
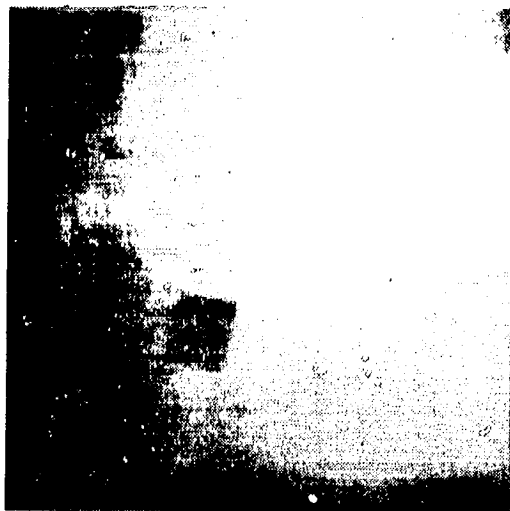
1. Frost, V. C.: Protection Against Meteoroids. NASA SP-8042, May 1970.
2. Humes, D. H.: Influence of the Bumper and Main Wall Material on the Effectiveness of Single Meteoroid Bumpers, NASA TN D-3104, Nov. 1965.
3. Anon.: Meteoroid Environment Model - 1969 (Near Earth to Lunar Surface). NASA SP-8013, Mar. 1969.
4. Anon.: Meteoroid Environment Model - 1970 (Interplanetary and Planetary). NASA SP-8038, Oct. 1970.
5. Anon.: The October 1973 Space Shuttle Traffic Model. NASA TM X-64751 Revision 2, Jan. 1974.

TABLE I. - DAMAGE TO SHUTTLE ORBITER LESS MATERIAL

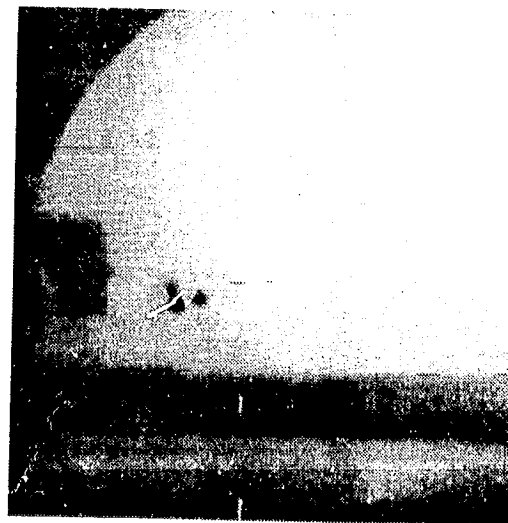
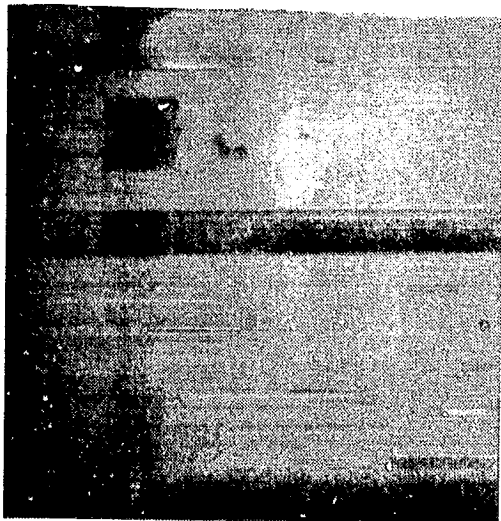
TARGET NUMBER	RUN NUMBER	PROJECTILE						IMPACT SITE FROM EDGE mm	TARGET		HOLE SIZE mm
		MATERIAL	SHAPE	SIZE mm	MASS mg	VELOCITY km/s	ENERGY J		AREA DAMAGED FRONT mm <sup>2</sup>	BACK mm <sup>2</sup>	
3-76	0328772	nylon	cylinder	2.11 dia. 1.52 long	5.1	5.4	74	34	153	213	12.8
3-77	0329772	nylon	sphere	1.52 dia.	2.3	5.7	37	29	69	104	3.4
3-73	0411772	nylon	cylinder	1.52 dia. 1.17 long	2.4	5.3	34	15	92	121	4.6
3-72	0428771	nylon	cylinder	1.00 dia. 0.79 long	0.71	5.5	11	26	35	52	-
3-80	0405771	nylon	cylinder	0.76 dia. 0.64 long	0.33	4.3	3	34	18.4	-	-
3-74	0429771	glass	sphere	0.27 dia.	0.024	5.4	0.3	32	3.4	-	-
3-70	0408771	glass	sphere	0.25 dia.	0.019	*	*	34	2.1	-	-
3-78	0404772	nylon	cylinder	0.76 dia. 0.64 long	0.33	1.2	0.2	32	2.2	-	-
3-71	0408772	glass	sphere	0.17 dia.	0.006	6.6	0.1	**	**	**	**

\* No measurement of velocity was obtained for this run. It is estimated from the loading conditions of the gun that the velocity was between 5 km/s and 6 km/s and that the energy was about 0.5 J.

\*\* This specimen was struck by trash which created more damage than was expected from the projectile.



(a) projectile launched at specimen 3-73



(b) projectiles launched at specimen 3-74

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Figure 1.- Photographs of the projectiles taken in flight to verify projectile integrity and to measure projectile velocity. Photographs do not have the same magnification.

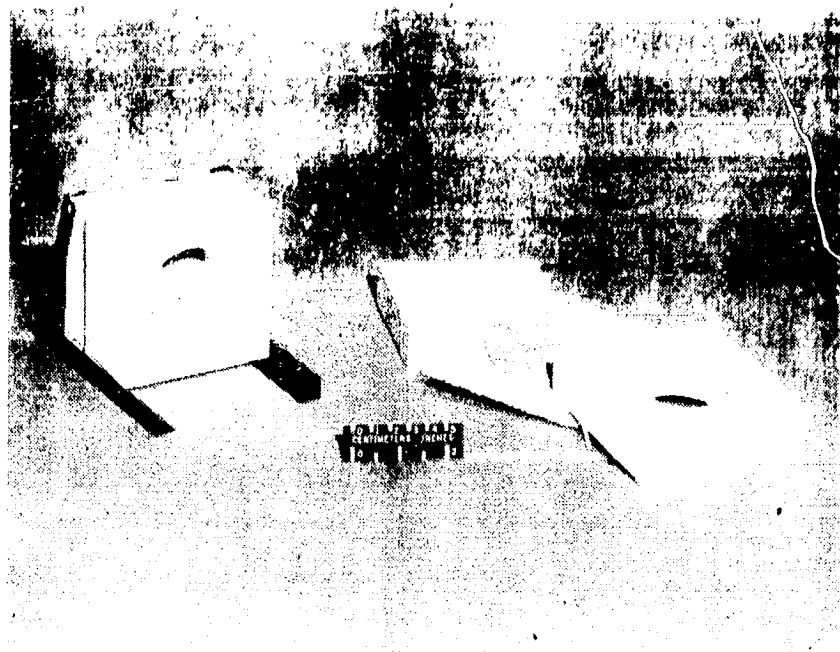
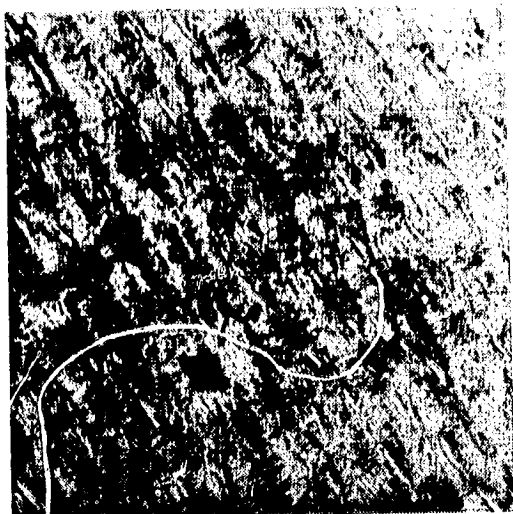
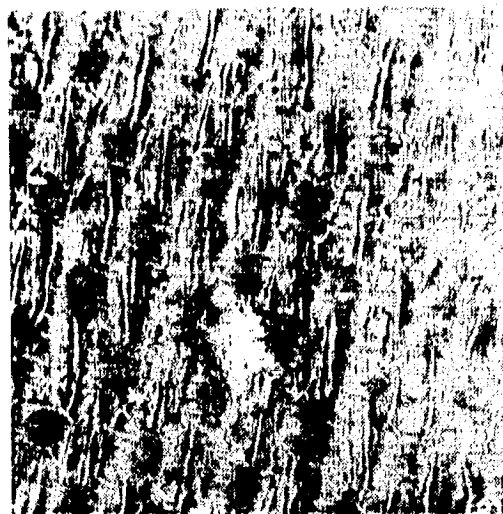


Figure 2.- Photograph of the target holder.

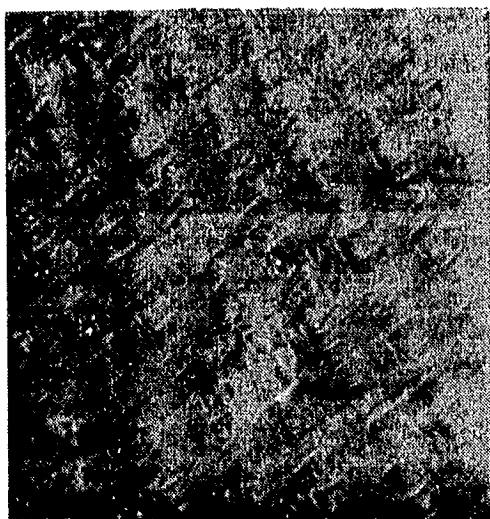
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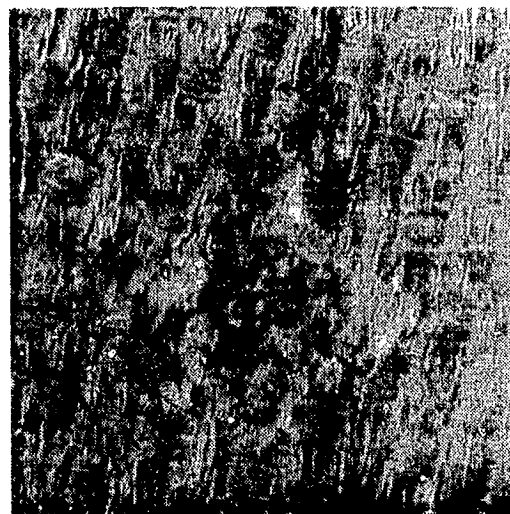
(a) specimen 3-78  
0.2 J



(b) specimen 3-70  
0.3 J



(c) specimen 3-74  
0.3 J



(d) specimen 3-80  
3 J

← 10 mm →

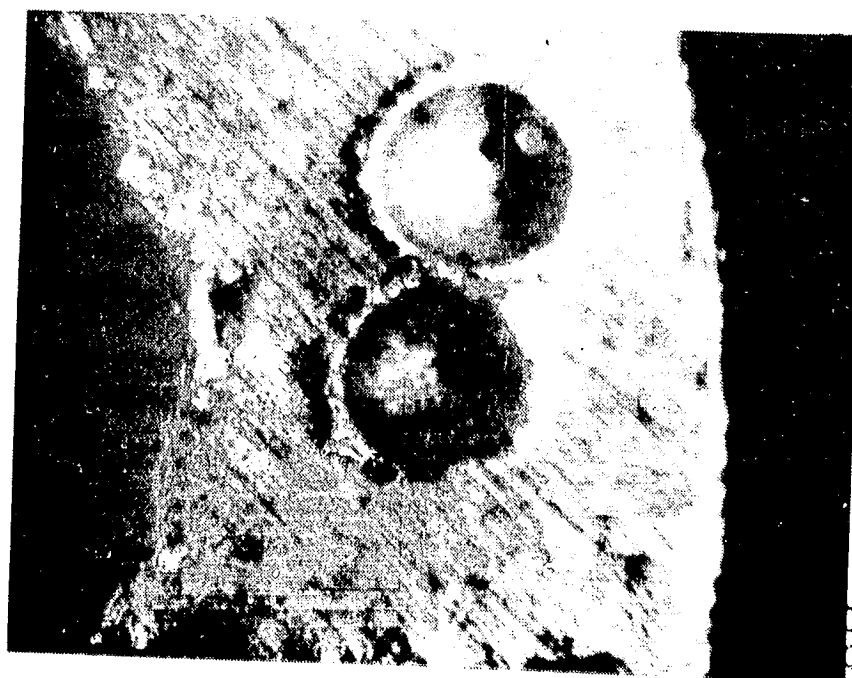
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Figure 3.- Photographs of the front surface of specimens struck by  
projectiles with kinetic energy of 3 J or less.



(a) LESS material specimen 3-74  
0.3 J

1 mm



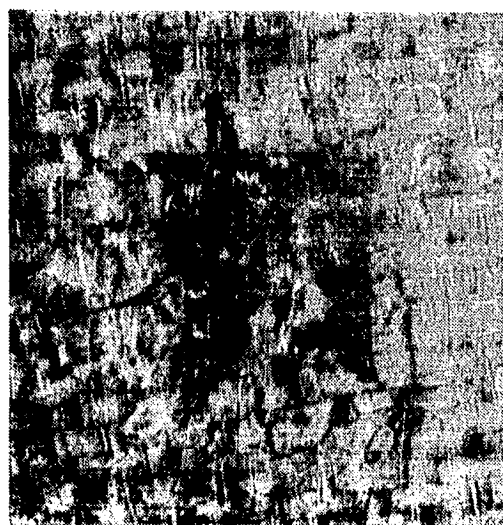
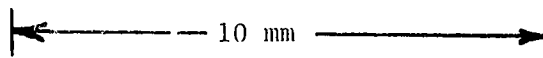
(b) cold rolled steel  
0.3 J

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Figure 4.- Photographs of damage caused by 0.27 mm glass projectiles  
at 5.4 km/s.



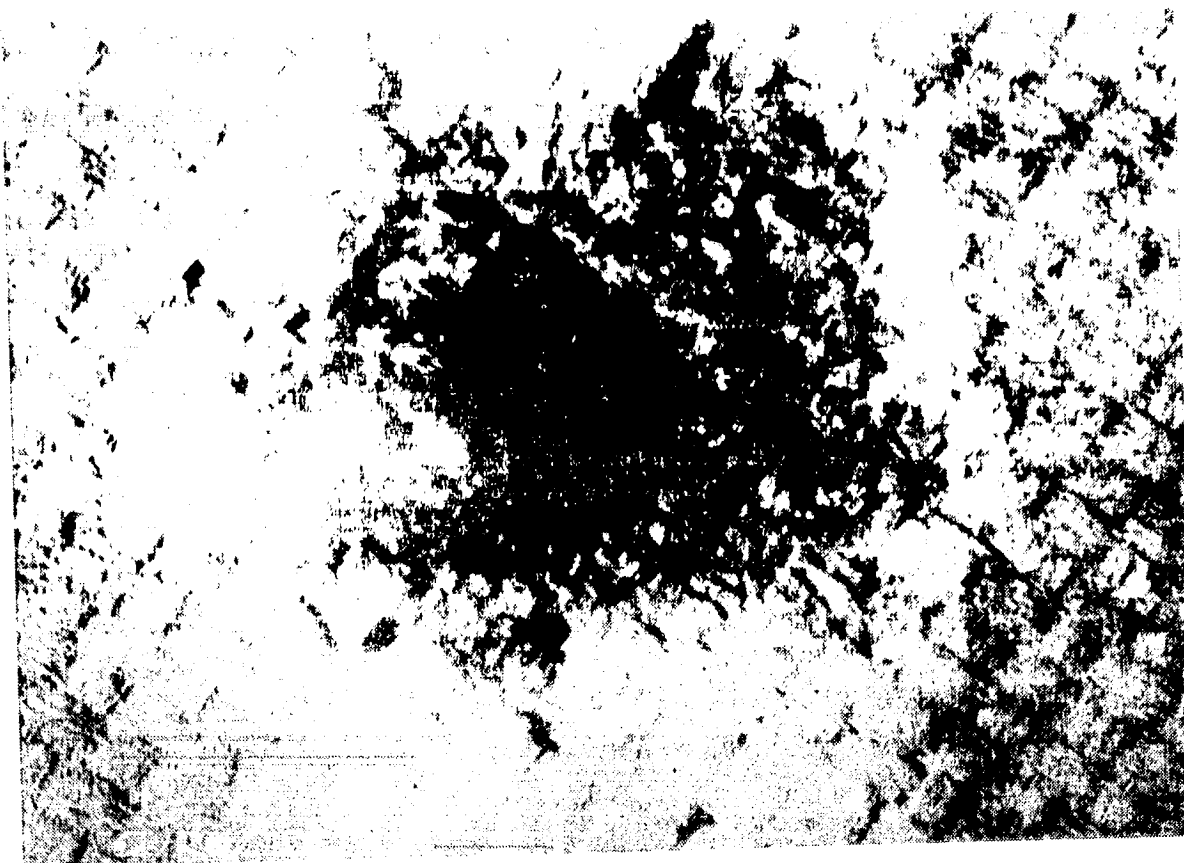
(a) front surface



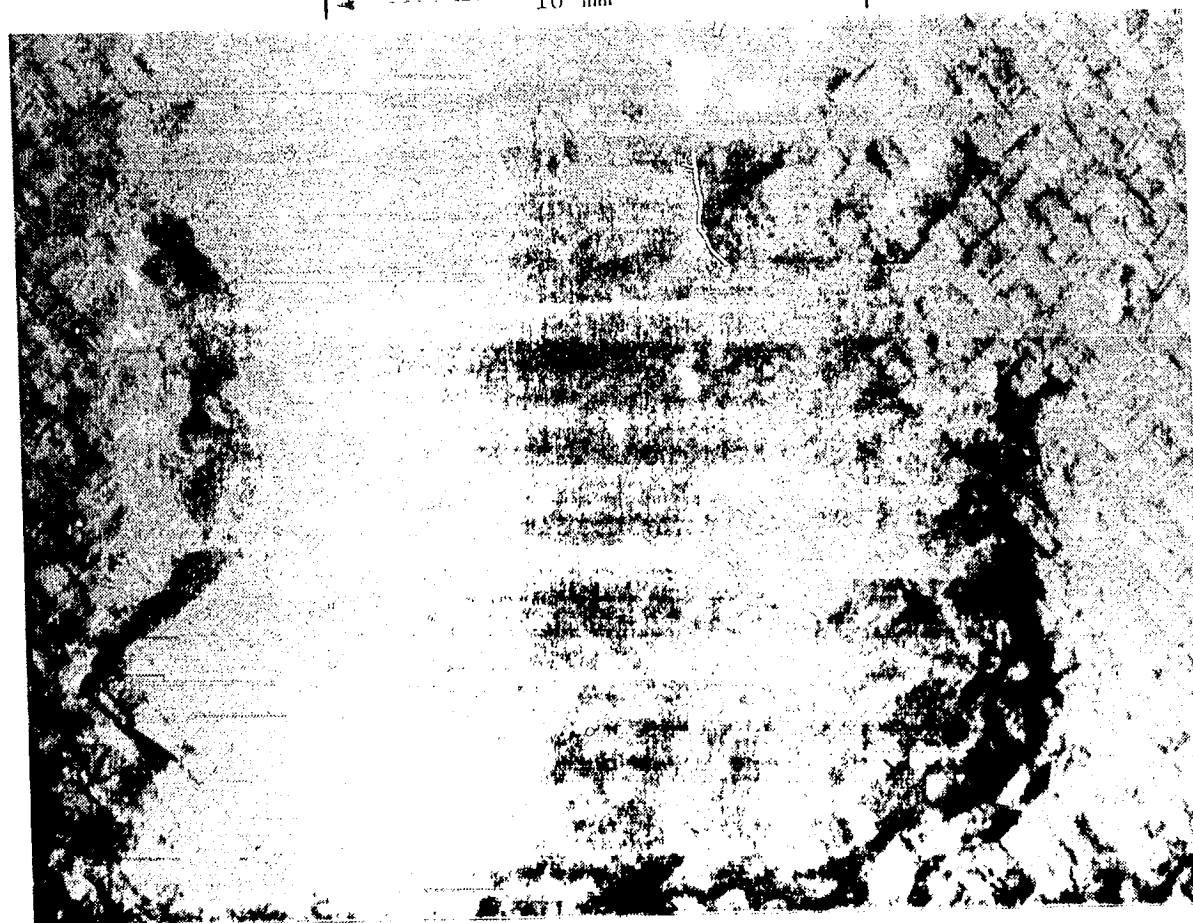
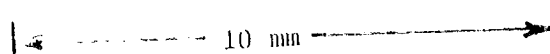
(b) back surface

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Figure 5.- Photographs of specimen 3-72. Kinetic energy of projectile was 11 J.



front surface

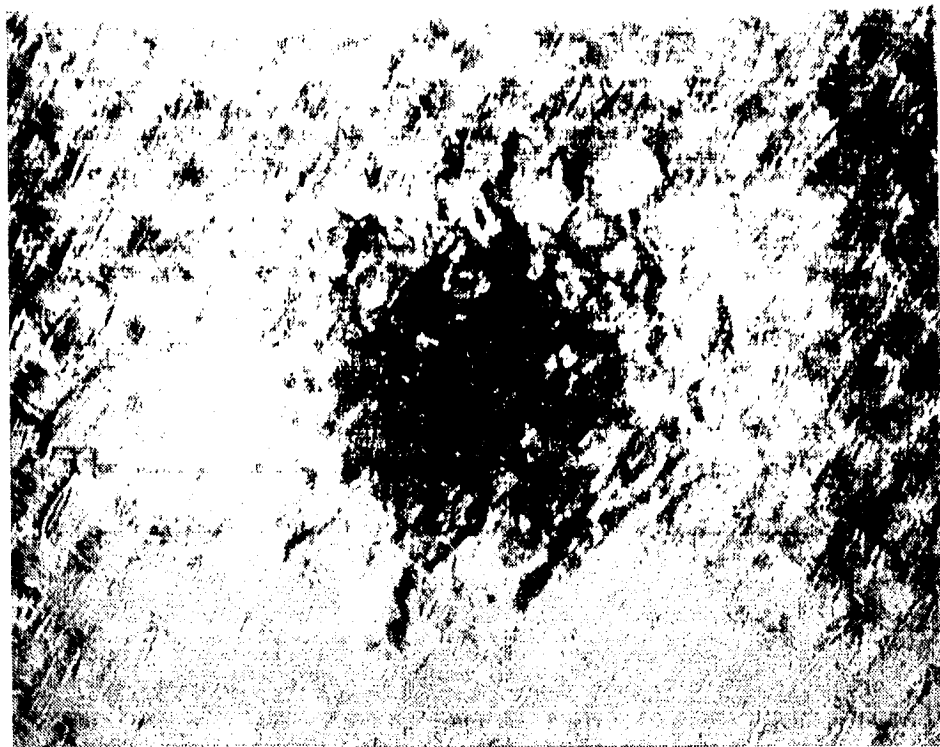


back surface

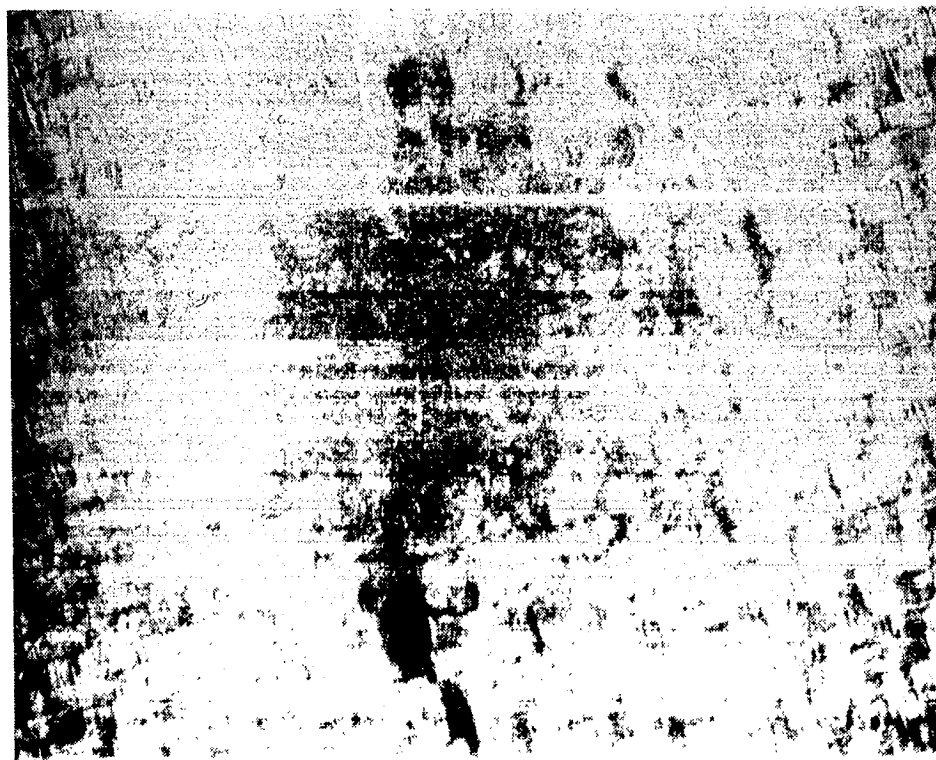
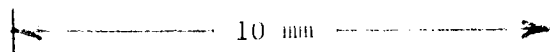
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Figure 6(a).-- Photographs of front and back surface of specimen 3-76.  
Kinetic energy of the projectile was 74 J.





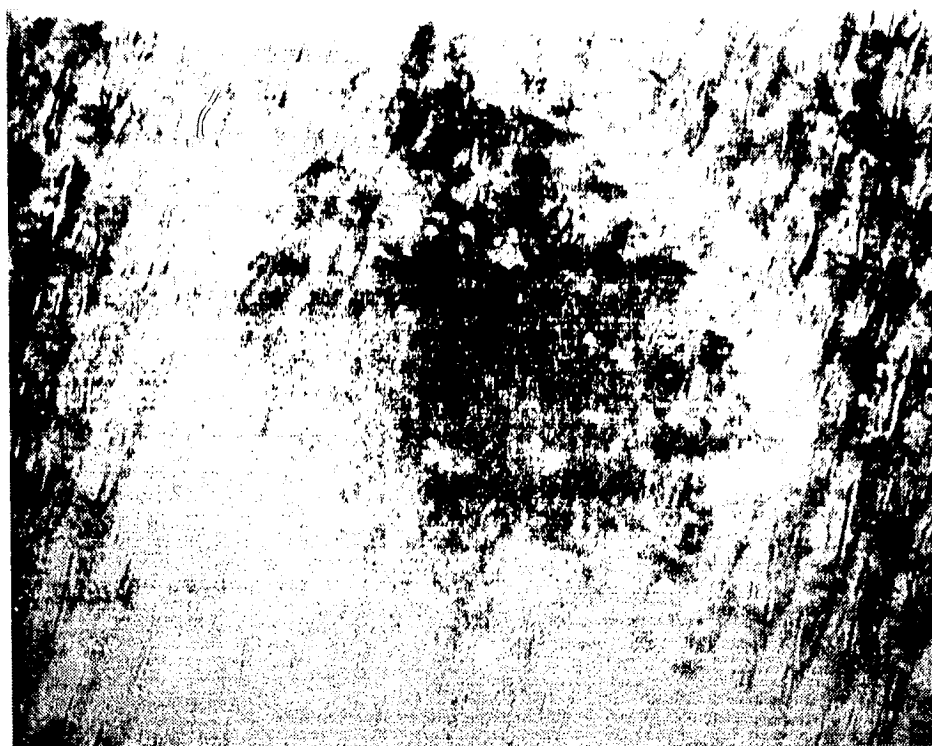
front surface



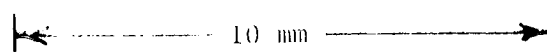
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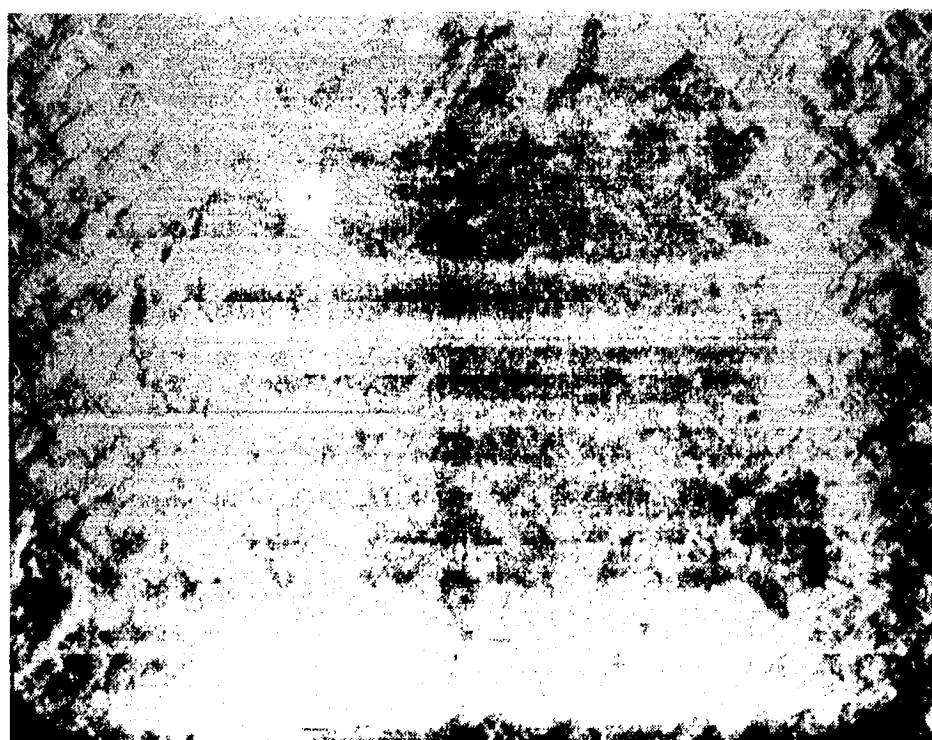
Figure 6(b). Photographs of front and back surface of specimen 3-77.  
Kinetic energy of the projectile was 37 J.



front surface

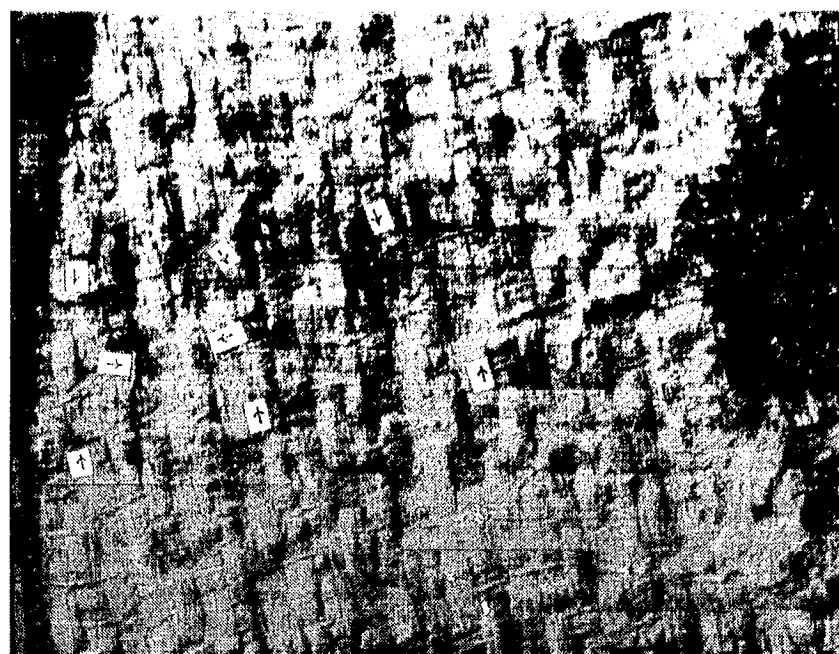


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back surface

Figure 6(c).- Photographs of front and back surface of specimen 3-73.  
Kinetic energy of the projectile was 34 J.



(a) back surface

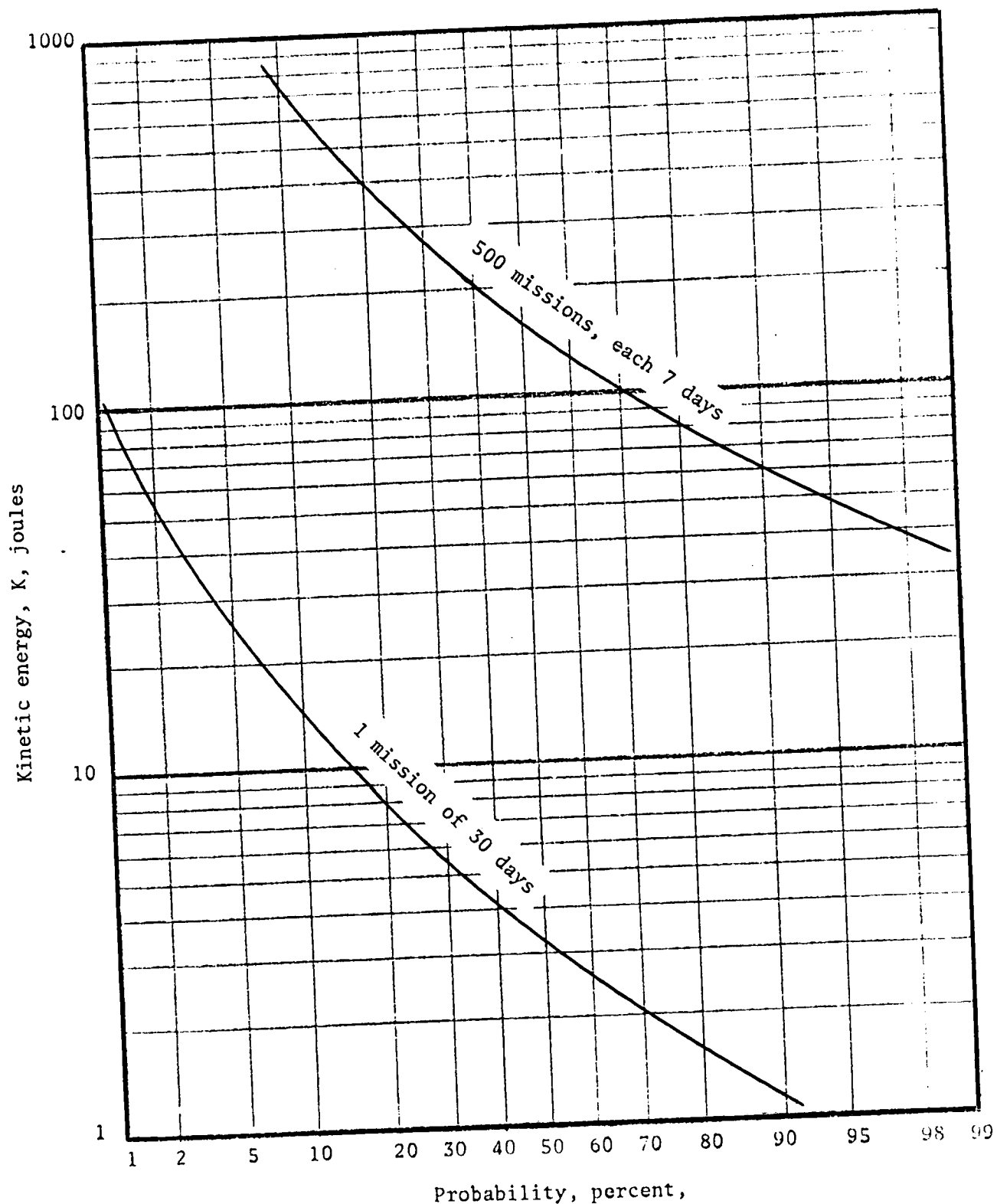
← 10 mm →



(b) edge

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Figure 7.- Photographs of specimen 3-73 showing cracks on the back surface and edge.



that a meteoroid with kinetic energy exceeding K will strike the nose or leading edge of a shuttle orbiter.

Fig.8. The kinetic energy of meteoroids expected to strike the leading edge and nose of the Shuttle Orbiter.

1. Report No. TM X-74039		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle HYPERVELOCITY IMPACT TESTS ON SPACE SHUTTLE ORBITER THERMAL PROTECTION MATERIAL				5. Report Date June 1977	
				6. Performing Organization Code 6460	
7. Author(s) Donald H. Humes				8. Performing Organization Report No. TM X-74039	
9. Performing Organization Name and Address National Aeronautics and Space Administration Hampton, Virginia 23665				10. Work Unit No. 506-16-36-03	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546				13. Type of Report and Period Covered Technical Memorandum	
				14. Sponsoring Agency Code	
15. Supplementary Notes Interim technical information release, subject to possible revision and/or later formal publication.					
16. Abstract  Hypervelocity impact tests were conducted to simulate the damage that meteoroids will produce in the Shuttle Orbiter leading edge structural subsystem material. The nature and extent of the damage is reported and the probability of encountering meteoroids with sufficient energy to produce such damage is discussed.					
17. Key Words (Suggested by Author(s)) (STAR category underlined) Hypervelocity Impact Meteoroid Space Shuttle Thermal Protection				18. Distribution Statement  Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 19	
				22. Price* \$3.50	

The National Technical Information Service, Springfield, Virginia 22161

\* Available from